STABLE INTERNATIONAL ENVIRONMENTAL AGREEMENTS FOR CORRELATED POLLUTANTS

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ABSTRACT

We examine the stability of international environmental policy schemes when sovereign nations set policies to control both greenhouse gas emissions and traditional air pollutants. An international environmental policy scheme is defined to be stable if no country can obtain higher payoffs under other international environmental policy schemes. We show that when regional transnational air pollution damages are large relative to climate change damages, there are many efficient and stable international environmental policy schemes in which all nations belong to coalitions, the coalitions are completely interconnected and the income transfers promoted within all coalitions follow the Nash bargaining formula.

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1. Introduction

Recent scientific evidence shows that mitigating greenhouse gases and controlling air pollutants are two closely related tasks.[1] Many greenhouse gases and air pollutants share common sources and hence changes in the activity levels of these sources affect both types of pollutants. Consider the burning of fossil fuels, which is not only the largest source of carbon dioxide emissions, but also generates high emissions of traditional air pollutants such as sulfur dioxide, nitrogen oxides, volatile organic compounds and particulate matter. It follows that enhanced fuel efficiency can reduce both types of pollutants. The linkage between the two types of pollutants is also observed in abatement spillovers, in the sense that technical measures of abatement aiming at reducing one type of pollutant may reduce or increase the other type of pollutant. For instance, selective catalytic reduction (SCR) on gas boilers reduces both methane – a greenhouse gas – and nitrogen oxides (EEA, 2004).

Both greenhouse gases and conventional air pollutants cause transnational environmental damages. Greenhouse gases emitted by every country add to the atmospheric concentration of these gases and lead to global warming. Hence, international coordination of sovereign nations is needed to tackle climate change. Under the Kyoto Protocol to the United Nations Framework Convention on Climate Change, which entered into force in 2005, the industrialized member countries commit to meeting their greenhouse gas emission reduction targets over the period of 2008-2012. Air pollutants such as sulfur dioxide, nitrogen oxides, volatile organic compounds and particulate matter can travel far from their original source with prevailing winds and lead to transboundary acid rain, ground level ozone, or smog problems in many regions of the world. International environmental agreements (IEAs) have been formed around the globe to mitigate

[1] See, e.g., IPCC (2001), EEA (2004), Bollen et al. (2009), and Defra (2010).

transboundary air pollutions. For example, the Convention on Long Range Transboundary Air Pollution (CLRTAP), which entered into force in 1983, together with eight subsequent protocols to the Convention, aims to reduce sulfur dioxide emissions, nitrogen oxides emissions and other transboundary air pollutants in countries in the United Nations Economic Commission for Europe (UNECE) region. In North America, Canada and the United States signed in 1991 the Canada-United States Air Quality Agreement to deal with transboundary acid rain problems. The two countries signed the Ozone Annex to the Agreement in 2000 to reduce ground-level ozone.

Conventional wisdom suggests that a Pareto efficient climate change mechanism requires the participation and cooperation of all countries emitting greenhouse gases.[2] The uncertainty of whether the Kyoto Protocol or a protocol beyond 2012 can achieve broad participation of major emitting countries, the correlated global warming and transboundary air pollution problems, and the formation of many IEAs for transboundary air pollution issues led Silva and Zhu (2011) to explore the potential of international environmental mechanisms for the efficient control of both greenhouse gases and transboundary air pollution, without requiring the formation of a fully participated grand coalition for climate change.[3] The authors consider coalition structures in which all nations belong to at least one IEA, there is no IEA containing all nations and there is complete interconnection among distinct IEAs. The authors demonstrate that national environmental policy making in a Nash non-cooperative manner can lead to Pareto efficiency if followed by proportionally equitable international income transfers within all coalitions. There is a large set of efficient international policy

[2] See, e.g., Caplan et al. (2003), for a discussion on the efficiency of an international carbon dioxide emissions permit market without global participation.

[3] See, e.g., Caplan and Silva (2005) and Silva and Zhu (2009), for efficient international environmental mechanisms that control both greenhouse gases and air pollution.

arrangements featuring coalitions with fewer than the total number of nations and producing national payoffs identical to those produced by the efficient grand coalition.

Due to the lack of supranational authorities with coercive power, the success of these efficient international mechanisms controlling both climate change and air pollution hinges on the voluntary participation and compliance of the sovereign nations. In providing the global public good of mitigating climate change, free riding incentives may prevail and lead individual countries to defect from an efficient mechanism. The task of the current paper is to go beyond the efficiency issue to investigate the stability of these efficient coalition structures.

Before we present our notion of stability of an international environmental mechanism, we identify two different notions of stability in the literature on the formation of IEAs: internal-external stability and γ-core stability. According to the γ-core concept that originates from cooperative game theory, a coalition lies in the γ-core of an IEA game if any individual country or group of countries cannot obtain higher payoffs deviating from the coalition. In face of deviation, the other coalition members will give up cooperation completely and choose their individual emission abatement strategies in a Nash non-cooperative manner. This strand of the IEA literature considers asymmetric countries and shows that the efficient grand coalition can be stable with implementation of international income transfer schemes (e.g., Chander and Tulkens, 1995, 1997, 2006; Eyckmans and Tulkens, 2003). Another strand of the IEA literature initiated by Carraro and Siniscalco (1993) and Barrett (1994) uses the stability concept developed by d'Aspremont et al. (1983) for cartel formation in a non-cooperative game framework.[4] A coalition is said to be stable if it is internally stable – no coalition member has an incentive to deviate, and externally stable – no outsider

[4] See, e.g., Finus (2008), for a recent review of both strands of the literature.

has an incentive to join the coalition. It is assumed that all countries are identical and that the coalition members cooperatively choose their abatement strategies to maximize collective welfare after they make membership decisions non-cooperatively. When defection occurs, the remaining coalition members will keep cooperation under the coalition. This branch of research shows that the grand coalition which would generate large welfare gains compared with a Nash non-cooperative situation is generally not likely to be stable. More recently, authors like Eyckmans and Finus (2003) show that stable coalition structures with multiple and non-overlapping IEAs can perform better in terms of welfare and abatement levels than a single coalition.

A key difference in the modeling between these two strands of research is how a deviator expects the other coalition members will respond to its defection. The γ-core theory assumes that a potential deviator expects the other members will break into singletons. This expectation of losing cooperation completely and entering the Nash equilibrium deters deviation and is inductive to the stability of the grand coalition. The d'Aspremont stability assumes that the other members will stay in the coalition and reduce emissions as a group. The grand coalition is hence usually unstable because a country can see a higher payoff generated by free riding on other countries' emission abatement efforts. Instead of placing such exogenous assumptions on the reactions of other coalition members, a number of researchers have introduced the idea of farsightedness into the IEA stability analysis.[5] When a country considers deviating from an IEA, it can fully foresee how the other countries may respond even at many steps away and what equilibrium coalition structures may emerge from its defection. The country makes decision by comparing its status quo welfare with welfare under potential

[5] See, among others, Chwe (1994), Mariotti (1997), Xue (1998) and Mariotti and Xue (2003) for the notion of farsighted stability in abstract settings.

final equilibrium outcomes. Chander (2003) shows if countries are farsighted, they will indeed break into singletons in response to deviation as suggested by the γ -core assumption and the grand coalition is farsightedly stable. Eyckmans (2001), Diamantoudi and Sartzetakis (2002), and Osmani and Tol (2009) demonstrate that farsighted stable coalitions with either identical or asymmetric players can achieve higher welfare and environmental quality than the d'Aspremont stable coalitions with myopic countries.

Our approach to the IEA stability issue differs from the previous work in three significant ways. First, we do not require countries to be either myopic or farsighted; or if countries are myopic, we do not impose an exogenous coalition structure at the next step of deviation. Accordingly, we define a coalition structure as a stable one if any individual country, or group of countries, could not find itself better off under any other coalition structures. This notion is essentially one of a coalition-proof Nash equilibrium which accounts for both individual and group rationality. We explore conditions under which an efficient coalition structure is stable in this sense. Without making assumptions on how other countries react to deviation, the stable coalition structures identified by us satisfy the d'Aspremont stability, γ -core stability and farsighted stability.

Secondly, we take into account policy making on both global climate change (i.e., global warming) and regional transnational air pollution (i.e., acid rain). As we will demonstrate, concerns over regional transnational air pollution problems can greatly impact a nation's deviation decision. When a nation considers defecting from an efficient coalition structure, it has to weigh the benefits of free riding on other countries' greenhouse gas emission reductions against the losses due to higher continental air pollution. It is indeed the joint policy making to reduce global and regional pollution damages that overcomes the free riding incentives in fighting climate change and allows an efficient coalition structure to be stable. Without taking into account regional transnational damages, it is hard for an efficient coalition structure such as the grand coalition to be stable in the d'Aspremont sense.

Thirdly, unlike Eyckmans and Finus (2003), we allow the formation of multiple IEAs with overlapped members, which enables us to derive a set of many efficient and stable coalition structures. The connectedness property of the efficient and stable coalition structures, which is the requirement that each player to be linked directly or indirectly to every other player, is fundamental. It enables the benefits of regional policy coordination to be fully incorporated into the analysis of the costs and benefits of global policy coordination.

We show that the efficiency results of Silva and Zhu (2011) hold when the payoff function of the income-transfer agency of a coalition follows the Nash bargaining form. We find that the stability of an efficient coalition structure depends on the relative magnitude of damages caused by regional (i.e., continental) air pollution and global climate change. When continental air pollution damages are large, a country may find it not profitable to deviate from an efficient coalition structure and act as a singleton because it will lose the benefits of reducing continental air pollution and the loss caused by increased continental air pollution outweighs the benefits of free riding on other countries' greenhouse gas emissions abatement.

The paper is organized as follows. Section 2 builds the basic model. Section 3 describes eight international environmental policy schemes. Section 4 discusses the stability of the efficient coalition structures. Section 5 concludes the paper.

2. The Basic Model

Consider a world consisting of four identical nations indexed $i = 1,...,4$ and two regions, North America and Europe. Nations 1 and 2 are located in North America and nations 3 and 4 are located in Europe. Normalizing the population in each country to unity, we write the representative consumer's utility in nation i

as $u_i = x_i + v(e_i) - a_i^2 - sg^2$, where x_i, e_i, a_i and g are respectively quantities consumed of a numeraire good, energy, acidic deposition and a greenhouse gas. The consumer's benefit from energy consumption is denoted $v(e_i) \equiv be_i - ce_i^2$, where b and c are positive parameters and we will have more discussions on the values of b and c later. We assume that one unit of energy consumption leads to one unit of sulfur dioxide emissions and one unit of emissions of the greenhouse gas. The sulfur emissions flow in both directions across the borders of the USA and Canada and of the two European nations.

Let the parameter α denote the fraction of nation j's sulfur emissions that deposit in nation j, $j = 1,2$. The fraction of nation j's sulfur emissions that travel to nation $-j$ in the same region is hence $1-\alpha$. Total sulfur depositions received by nation j are represented by the sum of its own sulfur depositions and sulfur spillovers from nation $-j$ in the same region, i.e., $a_j = \alpha e_j + (1-\alpha)e_{-j}$, $j = 1,2$, $-j = 1$ if $j = 2$ and vice-versa. Similarly, total sulfur depositions received by nation k is $a_k = \alpha e_k + (1-\alpha)e_{-k}$, $k = 3,4$, $-k = 3$ if $k = 4$ and vice-versa. For symmetry, we assume that $\alpha = 1/2$ and hence $a_1 = a_2 = (e_1 + e_2)/2$ and $a_3 = a_4 = (e_3 + e_4)/2$. The global quantity of greenhouse gas emissions is $g = \sum_{i=1}^{4} e_i$.

The parameter $s \in [0,1]$ is a sensitivity index, which measures how sensitive each nation is to the damage caused by climate change. Given the quantities of the emissions generated, the parameter s measures the relative magnitude of acid rain damage and climate change damage to a nation. For example, in any symmetric equilibrium, $e_i = a_i \equiv e$, $i = 1,..,4$, and $g = 4e$. Hence, the damage caused by acid rain to nation i is $a_i^2 = e^2$. The damage caused by climate change to nation i is

$sg^2 = 16se^2$. Thus, if $s = 1/16$, the damage caused by acid rain is equal to the damage caused by climate change to each nation. If $s = 1/8$, the greenhouse gas is twice harmful than acid rain.[6] We can therefore also refer to s as the damage-relativity index. We shall show below that the value of s is very important in determining the stability of the international environmental policy schemes.

3. International Environmental Policy Schemes

To identify stable international environmental policy schemes, we consider eight policy settings: setting 0, ({1},{2},{3},{4}); setting 1, ({1,2},{3,4}); setting 2, ({1,2},{3},{4}); setting 3, ({1,3},{2,4}); setting 4, ({1,3},{2},{4}); setting 5, ({1,2,3},{4}); setting 6, ({1,2,3,4}); setting 7, ({1,2},{2,3},{3,4}). We will show that settings 6 and 7 produce Pareto efficient allocations of world resources and settings 0 – 5 lead to inefficient allocations. Settings 0 – 5 represent all the inefficient policy schemes, because the inefficient policy schemes that are not included are "redundant" in the sense that each has an allocation that is identical to the allocation of one of settings 0 – 5 provided that the maximization problem solved by each coalition of two or more players has a unique solution. Consider,

[6] Keeping uncertainties of monetizing the impacts of climate change and air pollution in mind, let us take the US and EU as examples to gain some idea of the relative magnitude of the damages. An analysis by Chestnut and Mills (2005) of the US Acid Rain Program established by Title IV of the 1990 Clean Air Act Amendments estimates annual benefits of the program in 2010 at $122 billion in 2000 US dollars. According to the Second Perspective Report by the US EPA (2011), the benefits of the 1990 Clean Air Act Amendments of reducing nitrogen oxides, sulfur dioxide, volatile organic compounds and fine particles were estimated to reach almost $2 trillion in 2006 US dollars for the year 2020. In Nordhaus and Boyer (2000), the annual damage of a 2.5°C warming to the US was estimated to be $28 billion in 1990 dollars. For the EU, the health damages in 2020 due to baseline (2009) pollution of nitrogen oxides, sulfur dioxide, ammonia, volatile organic compounds and fine particles were estimated by AEA Technology plc (2011) to have a median value of €474.112 billion using the value of a life year (VOLY) approach based on PPP-adjusted UNECE average values in 2005 prices. Nordhaus and Boyer (2000) estimated the annual damage of a 2.5°C warming to OECD Europe to be 2.83% of GDP.

for example, the policy scheme ({1,2},{2,3}, {4}). We will discuss in subsection 3.6 that this policy scheme yields the same allocation as setting 5.

Setting 0: No IEA Formed

In this setting, the four nations act individually in a Nash non-cooperatively fashion. The budget constraint of the representative consumer in nation i is

$$x_i + e_i = w,\ i = 1,...,4, \tag{1a}$$

where w denotes national income and is assumed to be the same across nations. We can hence write nation i's numeraire consumption as $x_i = w - e_i$, $i = 1,...,4$.

Taking energy consumption choices of all other countries as given, nation j, $j = 1,2,$ chooses $e_j \geq 0$ to maximize

$$w - e_j + e_j(b - ce_j) - [(e_1 + e_2)/2]^2 - s\left(\sum_{i=1}^{4} e_i\right)^2. \tag{1b}$$

Taking energy consumption choices of all other countries as given, nation k, $k = 3,4,$ chooses $e_k \geq 0$ to maximize

$$w - e_k + e_k(b - ce_k) - [(e_3 + e_4)/2]^2 - s\left(\sum_{i=1}^{4} e_i\right)^2. \tag{1c}$$

The first order conditions for an interior solution to the maximization of (1a) and (1b) respectively are

$$b - 2ce_j = 1 + a_j + 2sg,\ j = 1,2, \tag{2a}$$

$$b - 2ce_k = 1 + a_k + 2sg, k = 3,4. \tag{2b}$$

Equations (2a) and (2b) inform us that each nation equalizes the marginal benefit and marginal cost of energy consumption when deciding on the amount of energy consumption in the nation. Without participating in any IEA, a nation's marginal cost of energy consumption includes the amount of numeraire consumption the nation gives up and the marginal damages the nation suffers from acid rain and climate change.

Since $a_1 = a_2$, equations (2a) imply that $e_1 = e_2$ and $a_1 = a_2 = e_2 = e_1$. Similarly, equations (2b) imply that $e_3 = e_4$ and $a_3 = a_4 = e_4 = e_3$. Equations (2a) and (2b) can hence be rewritten as

$$(2c+1)e_j = b - 1 - 2sg,\ j = 1,2, \tag{2c}$$

$$(2c+1)e_k = b - 1 - 2sg, k = 3,4, \tag{2d}$$

which show that $e_j = e_k$ and thus $a_j = a_k$, $j = 1,2$ and $k = 3,4$. Letting $a \equiv a_i$, $i = 1,...,4,$ we have $a = e$ and $g = 4e$. Substituting these results into either equations (2c) or (2d) and solving for e yield

$$e_i^0 = e^0 = \frac{b-1}{1+2c+8s} = a^0 = a_i^0, \quad i = 1,..,4, \tag{3a}$$

where we use the superscript 0 to denote the value of a variable realized in the equilibrium in setting 0. The equilibrium quantity of greenhouse gas emissions and utilities are:

$$g^0 = \frac{4(b-1)}{1+2c+8s}, \tag{3b}$$

$$u_i^0 = u^0 = w + \frac{(c-8s)(b-1)^2}{(1+2c+8s)^2},\ i = 1,..,4. \tag{3c}$$

Equations (3a) inform us that $b > 1$ ensures an interior solution in each maximization problem in setting 0. As we shall demonstrate below (in particular in subsection 3.6), $b > 1$ and/or $c \geq 2.3028$ ensure interior solutions in all international policy settings. Hence, we assume that $b > 1$ and $c \geq 2.3028$ in all settings.

3.2 Setting 1: Continental Environmental Agreements

Throughout the paper, we assume that each IEA has an agency in charge of promoting international income transfers. The income-transfer agencies' payoff functions follow the Nash bargaining form and use u^0 as the status quo utility.

The income transfers are implemented after the nations make their energy consumption choices. We model the international environmental policy schemes in which IEAs are formed as two stage games with decentralized leadership, where the income-transfer agencies act as Stackelberg followers while the nations are assumed to be Stackelberg leaders in policy making. The equilibrium concept used for the two-stage games is subgame perfection.

In setting 1, nations 1 and 2 form a continental environmental agreement in North America and nations 3 and 4 form a continental environmental agreement in Europe. Let t_i denote the monetary transfer paid (if positive) or received (if negative) by nation i, $i=1,...,4$. We assume that $t_1+t_2=0$ and $t_3+t_4=0$. The budget constraint of the representative consumer in nation i is as follows:

$$x_i+e_i=w-t_i\,,\quad i=1,...,4, \tag{4a}$$

which allows us to express numeraire consumption in nation i as $x_i=w-t_i-e_i$, $i=1,...,4.$ The utility of a representative consumer can hence be written as

$$w-t_j-e_j+e_j\left(b-ce_j\right)-\left[\left(e_1+e_2\right)/2\right]^2-s\left(\sum_{i=1}^{4}e_i\right)^2,\quad j=1,2, \tag{4b}$$

$$w-t_k-e_k+e_k\left(b-ce_k\right)-\left[\left(e_3+e_4\right)/2\right]^2-s\left(\sum_{i=1}^{4}e_i\right)^2,k=3,4. \tag{4c}$$

We solve the two-stage policy game by backward induction. Consider the second stage of the game. The payoff of the income-transfer agency in North America is $\pi\left(u_1,u_2\right)=\left(u_1-u^0\right)\left(u_2-u^0\right)$ and the payoff of the income-transfer agency in Europe is $\pi\left(u_3,u_4\right)=\left(u_3-u^0\right)\left(u_4-u^0\right)$, where $u_j, j=1,2,$ is described by expression (4b) and $u_k, k=3,4,$ is described by expression (4c). Having observed the nations' choices of energy consumption in the first stage of the game and given $\{e_1,e_2,a_1,a_2,g\}$, the income-transfer agency in North America chooses

$\{t_1, t_2\}$ to maximize $\pi(u_1, u_2) = (u_1 - u^0)(u_2 - u^0)$, subject to the income redistribution constraint $t_1 + t_2 = 0.$ The first order conditions are $(u_1 - u^0) - (u_2 - u^0) = 0$ and $t_1 + t_2 = 0.$ Thus, $u_1 = u_2$ and

$$t_1(e_1, e_2) = [e_1(b - 1 - ce_1) - e_2(b - 1 - ce_2)]/2 = -t_2(e_1, e_2). \quad (5a)$$

Plugging equations (5a) into the national payoff functions (4b) implies that the transfers will lead both nations to maximize the average payoff function in North America as follows:

$$w + \left[e_1(b - 1 - ce_1) + e_2(b - 1 - ce_2) - a_1^2 - a_2^2 - 2sg^2 \right] / 2. \quad (5b)$$

In the first stage of the game, nation j, $j = 1,2,$ chooses $e_j \geq 0$ to maximize (5b), taking every other nation's choice of energy consumption as given. The first order condition for an interior solution is

$$b - 2ce_j = 1 + 2a_j + 4sg, \; j = 1,2. \quad (6a)$$

Since $a_1 = a_2,$ equations (6a) imply that $e_1 = e_2$. Hence, $a_1 = a_2 = e_2 = e_1$.

Applying similar reasoning, the first order condition for an interior solution that governs the behavior of nation $k, k = 3,4,$ in the first stage is

$$b - 2ce_k = 1 + 2a_k + 4sg, \; k = 3, 4. \quad (6b)$$

With $a_3 = a_4,$ equations (6b) imply that $e_3 = e_4$. Hence, $a_3 = a_4 = e_4 = e_3$. Equations (6) tell us that with participation in a continental environmental agreement, a nation chooses energy consumption so that the marginal benefit of energy consumption equals the marginal cost of energy consumption which includes the amount of numeraire consumption the nation gives up and the marginal damages the two nations in the continental agreement suffer from acid rain and climate change.

Combining equations (6a) and (6b), we find that $e_j = e_k$ and thus $a_j = a_k$, $j = 1,2,$ $k = 3,4.$ Hence $a = e$, $g = 4e$ and

$$e_i^{1*} = e^{1*} = \frac{b-1}{2(1+c+8s)} = a^{1*} = a_i^{1*}, \quad i = 1,...,4, \tag{7a}$$

where we use the superscript "$m*$" to denote the value of a variable realized in the equilibrium in setting $m, m = 1,...,7$. We also obtain the following equilibrium values in setting 1:

$$g^{1*} = \frac{2(b-1)}{1+c+8s}, i = 1,...,4, \tag{7b}$$

$$u_i^{1*} = u^{1*} = w + \frac{(1+c)(b-1)^2}{4(1+c+8s)^2}, \ i = 1,..,4. \tag{7c}$$

3.3 Setting 2: One Continental Environmental Agreement in North America

Suppose that there is one continental environmental agreement in North America and the two European nations do not join any coalition. In this setting, the behavior of the income-transfer agency and the two countries in North America is the same as in setting 1.

In the second stage of the game, the maximization problem of the income-transfer agency in North America leads to $u_1 = u_2$ and equations (5a).

In the first stage of the game, nation j, $j = 1,2,$ chooses $e_j \geq 0$ to maximize (5b), and nation k, $k = 3,4,$ chooses $e_k \geq 0$ to maximize (1c), taking energy consumption choices of other countries as given. The first order conditions for an interior solution are equations (6a) and (2b) respectively, which allow us to derive the following equilibrium values in setting 2:

$$e_j^{2*} = \frac{(1+2c-4s)(b-1)}{2(1+c)(1+2c)+8s(2+3c)} = a_j^{2*}, j = 1,2, \tag{8a}$$

$$e_k^{2*} = \frac{(1+c+2s)(b-1)}{(1+c)(1+2c)+4s(2+3c)} = a_k^{2*}, k = 3,4, \tag{8b}$$

$$g^{2*} = \frac{(4c+3)(b-1)}{(c+1)(2c+1)+4s(3c+2)}, \tag{8c}$$

$$u_j^{2*} = w + \frac{\left[(2c+1)^2(c+1) - 4s\left(4c^2+10c+5\right) - 16s^2(7c+5)\right](b-1)^2}{\left[2(c+1)(2c+1)+8s(3c+2)\right]^2}, \; j=1,2, \tag{8d}$$

$$u_k^{2*} = w + \frac{\left[4c(c+1)^2 - 4s\left(4c^2+6c+3\right) + 16s^2(5c+3)\right](b-1)^2}{\left[2(c+1)(2c+1)+8s(3c+2)\right]^2}, k = 3,4. \tag{8e}$$

The assumptions $b > 1,\ c \geq 2.3028$ and $s \in [0,1]$ ensure $e_j^{2*} > 0,\ j = 1,2.$

3.4 Setting 3: Two Bilateral Intercontinental Environmental Agreements

Suppose now that there are two bilateral intercontinental environmental agreements, one formed by nations 1 and 3 and the other formed by nations 2 and 4. Consider the bilateral agreement between nations 1 and 3. The payoff for the income-transfer agency of this agreement is $\pi(u_1, u_3) = \left(u_1 - u^0\right)\left(u_3 - u^0\right)$. Let t_{13} denote the monetary transfer paid (if positive) or received (if negative) by nation 1. The budget constraints of the representative consumers in nations 1 and 3 can respectively be written as

$$x_1 + e_1 = w - t_{13}, \tag{9a}$$

$$x_3 + e_3 = w + t_{13}, \tag{9b}$$

which allow us to write numeraire consumption in these two nations as $x_1 = w - t_{13} - e_1$ and $x_3 = w + t_{13} - e_3$, respectively.

In the second stage of the game, having observed the nations' choices of energy consumption in the first stage of the game and given $\{e_1, e_3, a_1, a_3, g\}$, the income-transfer agency for nations 1 and 3 chooses t_{13} to maximize

$$\left[w - t_{13} + e_1(b-1-ce_1) - a_1^2 - sg^2 - u^0\right]\left[w + t_{13} + e_3(b-1-ce_3) - a_3^2 - sg^2 - u^0\right]. \tag{10a}$$

The first order condition is $\left(u_1 - u^0\right) - \left(u_3 - u^0\right) = 0.$ Thus, $u_1 = u_3$, which implies that

$$t_{13}(e_1, e_3, a_1, a_3) = \{[e_1(b-1-ce_1) - a_1^2] - [e_3(b-1-ce_3) - a_3^2]\}/2. \qquad (10b)$$

Plugging equation (10b) into the national payoff functions implies that both nations wish to maximize the following average payoff function:

$$w + \left[e_1(b-1-ce_1) + e_3(b-1-ce_3) - a_1^2 - a_3^2 - 2sg^2\right]/2. \qquad (10c)$$

In the first stage of the game, nation h, $h = 1,3$, chooses $e_h \geq 0$ to maximize (10c), taking every other nation's choice of energy consumption as given. Applying similar reasoning, it can be easily shown that nation l, $l = 2,4$, chooses $e_l \geq 0$ in the first stage to maximize

$$w + \left[e_2(b-1-ce_2) + e_4(b-1-ce_4) - a_2^2 - a_4^2 - 2sg^2\right]/2, \qquad (10d)$$

taking all other nations' energy consumption choices as given. The first order conditions for an interior solution to the nations' maximization problems are

$$b - 2ce_i = 1 + a_i + 4sg, \quad i = 1,\ldots,4, \qquad (10e)$$

which inform us that the marginal cost of energy consumption to a nation joining a bilateral environmental agreement equals the amount of numeraire consumption given up, the marginal damage the nation suffers from acid rain, and the marginal damage the two nations in the bilateral agreement suffer from climate change. The system of equations (10e) leads to the following equilibrium values in setting 3:

$$e_i^{3*} = e^{3*} = \frac{b-1}{1+2c+16s} = a^{3*} = a_i^{3*}, \; i = 1,\ldots,4, \qquad (11a)$$

$$g^{3*} = \frac{4(b-1)}{1+2c+16s}, \qquad (11b)$$

$$u_i^{3*} = u^{3*} = w + \frac{c(b-1)^2}{(1+2c+16s)^2}. \qquad (11c)$$

3.5 Setting 4: One Bilateral Intercontinental Environmental Agreement

Consider the setting in which there is only one bilateral intercontinental environmental agreement formed by nations 1 and 3. In this setting, the behavior of nations 1 and 3 and their income-transfer agency is the same as in setting 3 described in subsection 3.4.

In the second stage of the game, the maximization problem of the income-transfer agency leads to $u_1 = u_3$ and equation (10b).

In the first stage of the game, nation h, $h = 1,3,$ chooses $e_h \geq 0$ to maximize (10c), nation 2 chooses $e_2 \geq 0$ to maximize (1b), and nation 4 chooses $e_4 \geq 0$ to maximize (1c), taking energy consumption choices of other countries as given. The first order conditions for an interior solution are equations (10e) for nation h, $h = 1,3,$ equation (2a) for nation 2 and equation (2b) for nation 4. We thus derive the following equilibrium values in setting 4:[7]

$$e_h^{4*} = \frac{(c-2s)(b-1)}{c(1+2c+12s)}, \quad h = 1,3, \tag{12a}$$

$$e_l^{4*} = \frac{(c+2s)(b-1)}{c(1+2c+12s)}, \quad l = 2,4, \tag{12b}$$

$$g^{4*} = \frac{4(b-1)}{1+2c+12s}, \ h = 1,3, \text{ and } l = 2,4, \tag{12c}$$

$$a_i^{4*} = a^{4*} = \frac{1}{2}\left(e_1^{4*} + e_2^{4*}\right) = \frac{b-1}{1+2c+12s}, i = 1,\ldots,4, \tag{12d}$$

$$u_h^{4*} = w + \frac{\left[c(c-16) - 2s(1-6c) - 28s^2\right](b-1)^2}{c(1+2c+12s)^2}, \quad h = 1,3, \tag{12e}$$

$$u_l^{4*} = w + \frac{\left[c(c-16) + 2s(1+6c) + 20s^2\right](b-1)^2}{c(1+2c+12s)^2}, \quad l = 2,4. \tag{12f}$$

[7] Please see Appendix A for the derivation of equations (12a) and (12b).

Given our assumptions that $b > 1$, $c \geq 2.3028$ and $s \in [0,1]$, we have $e_h^{4*} > 0$, $h = 1,3.$

3.6 Setting 5: Trilateral Intercontinental Environmental Agreement

Consider the setting in which there is a trilateral intercontinental environmental agreement formed by nations 1, 2 and 3. Nation 4 stays as a singleton. Let $t_l > 0$ denote the monetary transfer paid (if positive) or received (if negative) by nation l, $l = 1,2,3.$ We assume that $t_1 + t_2 + t_3 = 0$. The budget constraint of the representative consumer in nation l, $l = 1,2,3,$ can be written as

$$x_l + e_l = w - t_l. \tag{13}$$

Hence, numeraire consumption in nation l, $l = 1,2,3,$ is $x_l = w - t_l - e_l$.

The payoff for the income-transfer agency of the trilateral agreement is $\pi(u_1, u_2, u_3) = \prod_{l=1}^{3}(u_l - u^0)$, where $u_l = w - t_l + e_l(b - 1 - ce_l) - a_l^2 - sg^2, \quad l = 1,2,3.$

In the second stage of the game, having observed the nations' choices of energy consumption in the first stage of the game and given $\{e_1, e_2, e_3, a_1, a_2, a_3, g\}$, the income-transfer agency chooses $\{t_1, t_2, t_3\}$ to maximize $\pi(u_1, u_2, u_3)$, subject to $t_1 + t_2 + t_3 = 0$. The solution is given by $u_1 = u_2 = u_3$ and the constraint on the transfers. Thus, we obtain:

$$\begin{aligned} &t_1(e_1, e_2, e_3, a_1, a_2, a_3) \\ &= \{2[e_1(b - 1 - ce_1) - a_1^2] - [e_2(b - 1 - ce_2) - a_2^2] - [e_3(b - 1 - ce_3) - a_3^2]\}/3, \end{aligned} \tag{14a}$$

$$\begin{aligned} &t_2(e_1, e_2, e_3, a_1, a_2, a_3) \\ &= \{2[e_2(b - 1 - ce_2) - a_2^2] - [e_1(b - 1 - ce_1) - a_1^2] - [e_3(b - 1 - ce_3) - a_3^2]\}/3, \end{aligned} \tag{14b}$$

$$\begin{aligned} &t_3(e_1, e_2, e_3, a_1, a_2, a_3) \\ &= \{2[e_3(b - 1 - ce_3) - a_3^2] - [e_1(b - 1 - ce_1) - a_1^2] - [e_2(b - 1 - ce_2) - a_2^2]\}/3. \end{aligned} \tag{14c}$$

Plugging equations (14) into the national payoff functions show that nation l, $l=1,2,3,$ wishes to maximize the following average payoff function:

$$w+\left[(b-1)(e_1+e_2+e_3)-c\left(e_1^2+e_2^2+e_3^2\right)-a_1^2-a_2^2-a_3^2-3sg^2\right]\Big/3. \qquad (15)$$

In the first stage of the game, nation l, $l=1,2,3,$ chooses $e_l \geq 0$ to maximize (15), taking energy consumption choices of all other countries as given. The first order conditions for an interior solution are

$$b-2ce_j=1+2a_j+6sg,\ j=1,2, \qquad (16a)$$

$$b-2ce_3=1+a_3+6sg. \qquad (16b)$$

Equations (16a) and (16b) inform us that the transfers implemented in the trilateral agreement motivate each member country of the agreement to internalize the externalities caused by the greenhouse gas emissions within the three countries. Equations (16a) tell us that the two countries in North America also fully internalize continental externalities caused by acid rain.

The first order condition for an interior solution to the maximization problem solved by the stand alone nation 4 is described by equation (2b).

Equations (16a) imply that $e_1=e_2$. Hence, $a_1=a_2=e_2=e_1$ and $g=2e_1+e_3+e_4$. Plugging these results and the fact that $a_3=a_4=(e_3+e_4)/2$ into equations (16), we obtain the following equilibrium values in setting 5:

$$e_j^{5*}=a_j^{5*}=\frac{(1+2c-4s)(b-1)}{2[(1+c)(1+2c)+2s(7+10c)]},\ j=1,2, \qquad (17a)$$

$$e_3^{5*}=\frac{[c(1+c)-s(3+2c)](b-1)}{c[(1+c)(1+2c)+2s(7+10c)]}, \qquad (17b)$$

$$e_4^{5*}=\frac{[c(1+c)+3s(1+2c)](b-1)}{c[(1+c)(1+2c)+2s(7+10c)]}, \qquad (17c)$$

$$a_k^{5*}=\frac{2(1+c+2s)(b-1)}{(1+c)(1+2c)+2s(7+10c)},\ k=3,4, \qquad (17d)$$

$$g^{5*} = \frac{(3+4c)(b-1)}{(1+c)(1+2c)+2s(7+10c)}, \tag{17e}$$

$$u_l^{5*} = w + \frac{\left[c(1+c)(1+6c+6c^2) - 2s(3+8c-4c^2-12c^3) - 6s^2(1+2c)(17+22c)\right](b-1)^2}{6c\left[(1+c)(1+2c)+2s(7+10c)\right]^2}, l = 1,2,3, \tag{17f}$$

$$u_4^{5*} = w + \frac{\left\{c^2(1+c)^2 + s\left[3+2c+4c(1+c)(2+c)\right] + s^2(33+104c+84c^2)\right\}(b-1)^2}{c\left[(1+c)(1+2c)+2s(7+10c)\right]^2}. \tag{17g}$$

Our assumption $c \geq 2.3028$ originates from equation (17b), which says that $e_3^{5*} > 0$ for all $s \in [0,1]$ requires $b > 1$ and $c \geq 2.3028$.

Now consider the coalition structure ({1,2},{2,3},{4}). In this setting, there is a continental environmental agreement formed by nations 1 and 2 and a trans-continental environmental agreement formed by nations 2 and 3. Our previous analysis of the international income transfers informs us that the income transfers promoted in the continental agreement will lead to $u_1 = u_2$ and the income transfers promoted in the trans-continental agreement will lead to $u_2 = u_3$. Thus, $u_1 = u_2 = u_3$ and nations 1, 2 and 3 will be motivated to maximize the average payoff function of the three nations described by expression (15). The coalition structure ({1,2},{2,3},{4}) hence yields the same equilibrium allocation as the coalition structure ({1,2,3},{4}).

3.7 Setting 6: the Grand Coalition

If the Grand Coalition (GC) containing all four countries is formed, the budget constraint of the representative consumer in nation i is

$$x_i + e_i = w - t_i, \quad i = 1,\ldots,4, \tag{18}$$

where t_i denotes the monetary transfer paid (if positive) or received (if negative) by nation i under the GC and $\sum_{i=1}^{4} t_i = 0.$ We write numeraire consumption in nation i as $x_i = w - t_i - e_i$, $i = 1,\ldots,4.$

The payoff for the income-transfer agency in the GC is $\pi(u_1, u_2, u_3, u_4) = \prod_{i=1}^{4} (u_i - u^0)$, where $u_i = w - t_i + e_i\,(b - 1 - ce_i) - a_i^2 - sg^2$, $i = 1,\ldots,4.$

Having observed the nations' choices of energy consumption in the first stage of the game and taking $\{e_i, a_i, g\}_{i=1,\ldots,4}$ as given, the income-transfer agency in the second stage of the game chooses $\{t_i\}_{i=1,\ldots,4}$ to maximize $\pi(u_1, u_2, u_3, u_4)$, subject to $\sum_{i=1}^{4} t_i = 0.$ The solution is given by $u_1 = u_2 = u_3 = u_4$ and $\sum_{i=1}^{4} t_i = 0.$ Thus, we obtain

$$
\begin{aligned}
& t_1(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4) \\
& = 3\left[e_1(b - 1 - ce_1) - a_1^2\right]/4 \\
& - \left\{\left[e_2(b - 1 - ce_2) - a_2^2\right] + \left[e_3(b - 1 - ce_3) - a_3^2\right] + \left[e_4(b - 1 - ce_4) - a_4^2\right]\right\}/4,
\end{aligned} \tag{19a}
$$

$$
\begin{aligned}
& t_2(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4) \\
& = 3\left[e_2(b - 1 - ce_2) - a_2^2\right]/4 \\
& - \left\{\left[e_1(b - 1 - ce_1) - a_1^2\right] + \left[e_3(b - 1 - ce_3) - a_3^2\right] + \left[e_4(b - 1 - ce_4) - a_4^2\right]\right\}/4,
\end{aligned} \tag{19b}
$$

$$
\begin{aligned}
& t_3(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4) \\
& = 3\left[e_3(b - 1 - ce_3) - a_3\right]/4 \\
& - \left\{\left[e_1(b - 1 - ce_1) - a_1^2\right] + \left[e_2(b - 1 - ce_2) - a_2^2\right] + \left[e_4(b - 1 - ce_4) - a_4^2\right]\right\}/4,
\end{aligned} \tag{19c}
$$

$$
\begin{aligned}
& t_4(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4) \\
& = 3\left[e_4(b - 1 - ce_4) - a_4\right]/4 \\
& - \left\{\left[e_1(b - 1 - ce_1) - a_1^2\right] + \left[e_2(b - 1 - ce_2) - a_2^2\right] + \left[e_3(b - 1 - ce_3) - a_3^2\right]\right\}/4.
\end{aligned} \tag{19d}
$$

Plugging equations (19a) – (19d) into the national payoff functions imply that the four nations wish to maximize the following average payoff function:

$$w+\left[(b-1)\sum_{i=1}^{4}e_i-c\sum_{i=1}^{4}e_i^2-\sum_{i=1}^{4}a_i^2-4sg^2\right]\Big/4. \tag{19e}$$

In the first stage of the game, nation i, $i=1,...,4,$ chooses $e_i \geq 0$ to maximize (19e), taking energy consumption choices of all other countries as given. The first order conditions for an interior solution are

$$b-2ce_i=1+2a_i+8sg,\ i=1,...,4, \tag{20}$$

which state that the transfers implemented among the four nations have induced each nation to internalize all continental acid rain externalities and climate change externalities when making decisions on energy consumption. Equations (20) imply that $a=e,\ g=4e$, and we have the following equilibrium values in setting 6:

$$e_i^{6*}=e^{6*}=\frac{b-1}{2(1+c+16s)}=a^{6*}=a_i^{6*}, i=1,...,4, \tag{21a}$$

$$g^{6*}=\frac{2(b-1)}{1+c+16s}, \tag{21b}$$

$$u_i^{6*}=u^{6*}=w+\frac{(b-1)^2}{4(1+c+16s)}, i=1,...,4. \tag{21c}$$

3.8 Setting 7: Continental and Inter-continental Environmental Agreements

Suppose that there are two continental environmental agreements, one in North America and the other in Europe. The payoff of the income-transfer agency in North America is $\pi(u_1,u_2)=(u_1-u^0)(u_2-u^0)$ and the payoff of the income-transfer agency in Europe is $\pi(u_3,u_4)=(u_3-u^0)(u_4-u^0)$. Suppose that there is a trans-continental environmental agreement formed by nations 2 and 3. The payoff of the income-transfer agency in the trans-continental agreement is $\pi(u_2,u_3)=(u_2-u^0)(u_3-u^0)$.

As in setting 1, we let t_i denote the monetary transfer paid (if positive) or received (if negative) by nation i under the continental environmental agreements and assume $t_1 + t_2 = 0$ and $t_3 + t_4 = 0$. Let t_{23} denote the monetary transfer paid (if positive) or received (if negative) by nation 2 under the trans-continental agreement. The budget constraints of the representative consumers in the four nations are respectively

$$x_1 + e_1 = w - t_1, \tag{22a}$$

$$x_2 + e_2 = w - t_2 - t_{23}, \tag{22b}$$

$$x_3 + e_3 = w - t_3 + t_{23}, \tag{22c}$$

$$x_4 + e_4 = w - t_4. \tag{22d}$$

In the second stage of the game, having observed the nations' choices of energy consumption in the first stage of the game and taking $\{e_1, e_2, a_1, a_2, g\}$ and $\{t_{23}\}$ as given, the income-transfer agency in North America chooses $\{t_1, t_2\}$ to maximize

$$\left[w - t_1 + e_1(b - 1 - ce_1) - a_1^2 - sg^2 - u^0\right]\left[w - t_2 - t_{23} + e_2(b - 1 - ce_2) - a_2^2 - sg^2 - u^0\right], \tag{23a}$$

subject to $t_1 + t_2 = 0$. The first order conditions are $\left(u_1 - u^0\right) - \left(u_2 - u^0\right) = 0$ and $t_1 + t_2 = 0$. Thus, $u_1 = u_2$ and

$$t_1(e_1, e_2, t_{23}) = \{e_1(b - 1 - ce_1) - [e_2(b - 1 - ce_2) - t_{23}]\}/2 = -t_2(e_1, e_2, t_{23}). \tag{23b}$$

Taking $\{e_3, e_4, a_3, a_4, g\}$ and $\{t_{23}\}$ as given, the income-transfer agency in Europe chooses $\{t_3, t_4\}$ to maximize

$$\left[w - t_3 + t_{23} + e_3(b - 1 - ce_3) - a_3^2 - sg^2 - u^0\right]\left[w - t_4 + e_4(b - 1 - ce_4) - a_4^2 - sg^2 - u^0\right], \tag{23c}$$

subject to $t_3 + t_4 = 0$. The first order conditions are $(u_3 - u^0) - (u_4 - u^0) = 0$ and $t_3 + t_4 = 0$. Thus, $u_3 = u_4$ and

$$t_3(e_3, e_4, t_{23}) = \{[e_3(b-1-ce_3) + t_{23}] - e_4(b-1-ce_4)\}/2 = -t_4(e_3, e_4, t_{23}). \qquad (23d)$$

Taking $\{e_2, e_3, a_2, a_3, g\}$ and $\{t_2, t_3\}$ as given, the income-transfer agency of the trans-continental agreement chooses t_{23} to maximize

$$[w - t_2 - t_{23} + e_2(b-1-ce_2) - a_2^2 - sg^2 - u^0][w - t_3 + t_{23} + e_3(b-1-ce_3) - a_3^2 - sg^2 - u^0]. \qquad (23e)$$

The first order condition is $(u_2 - u^0) - (u_3 - u^0) = 0$. Thus, $u_2 = u_3$ and

$$t_{23}(e_2, e_3, a_2, a_3, t_2, t_3) = \{[e_2(b-1-ce_2) - t_2 - a_2^2] - [e_3(b-1-ce_3) - t_3 - a_3^2]\}/2. \qquad (23f)$$

Combining equations (23b), (23d) and (23f) yields

$$\begin{aligned} &t_{23}(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4) \\ &= \{[e_1(b-1-ce_1) - a_1^2] + [e_2(b-1-ce_2) - a_2^2]\}/2 \\ &- \{[e_3(b-1-ce_3) - a_3^2] + [e_4(b-1-ce_4) - a_4^2]\}/2, \end{aligned} \qquad (24a)$$

$$\begin{aligned} &t_1(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4) \\ &= 3[e_1(b-1-ce_1) - a_1^2]/4 \\ &- \{[e_2(b-1-ce_2) - a_2^2] + [e_3(b-1-ce_3) - a_3^2] + [e_4(b-1-ce_4) - a_4^2]\}/4 \\ &= -t_2(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4), \end{aligned} \qquad (24b)$$

$$\begin{aligned} &t_3(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4) \\ &= \{[e_1(b-1-ce_1) - a_1^2] + [e_2(b-1-ce_2) - a_2^2] + [e_3(b-1-ce_3) - a_3^2]\}/4 \\ &- 3[e_4(b-1-ce_4) - a_4^2]/4 \\ &= -t_4(e_1, e_2, e_3, e_4, a_1, a_2, a_3, a_4). \end{aligned} \qquad (24c)$$

Plugging equations (24a) – (24c) into the national payoff functions imply that the four nations wish to maximize the average payoff function (19e).

In the first stage of the game, nation i, $i = 1,...,4,$ chooses $e_i \geq 0$ to maximize (19e), taking energy consumption choices of all other countries as given. The first order conditions for an interior solution are given by equations (20). Like the GC, the coalition structure ({1,2},{2,3},{3,4}) leads each country to internalize all environmental externalities. The equilibrium amounts of emissions are described by equations (21a) and (21b), and the equilibrium payoffs for the nations are given by equations (21c). Hence, both the GC and the international policy setting ({1,2},{2,3},{3,4}) produce Pareto efficient allocations of world resources. We summarize the efficiency results in subsections 3.7 and 3.8 in the following proposition:

Proposition 1. The subgame perfect equilibrium for the international policy game in which there is a Grand Coalition containing all four nations is Pareto efficient. The subgame perfect equilibrium for the international policy game with a coalition structure ({1,2},{2,3},{3,4}) is also Pareto efficient. The payoffs of the nations are the same in these two efficient international policy arrangements.

4. Stability

Similar to Silva and Zhu (2011), we find that there are many efficient international policy arrangements like ({1,2},{2,3},{3,4}) that do not require the establishment of the GC but successfully induce the nations to fully internalize the environmental externalities. In such arrangements, all nations' payoff levels must be connected through coalitions with overlapping members which function as bridges between coalitions. For example, consider a coalition structure ({2,3,4},{1,2}), under which nations 2, 3 and 4 form a trilateral trans-continental agreement and nations 1 and 2 form a bilateral continental agreement. The income transfers promoted in the trilateral agreement equalize the payoffs of nations 2, 3 and 4. The income transfers implemented in the continental agreement equalize the payoffs of nations 1 and 2. Since nation 2 joins both agreements, all four nations' welfare levels are equalized in equilibrium and every nation makes efficient choices of energy consumption to maximize global welfare.

We define a coalition structure as a stable one if the payoff of every nation produced by the structure is no lower than the nation's payoff produced by any other coalition structure. Since all nations' payoffs are equalized in an efficient international policy arrangement, all efficient policy arrangements yield the same set of national payoffs. Thus, there is no loss in generality in focusing our attention on one efficient setting to discuss the stability of all efficient policy arrangements. We shall examine the stability of setting 7 with the coalition structure ({1,2}, {2,3}, {3,4}).

4.1 Stability Conditions

Setting 7 is stable if no country or group of countries can be better off deviating from it. Comparing equations (7c) and (21c) shows that

$$u^{7*} = u^{1*}, \text{ if } s = 0; \text{ and } u^{7*} > u^{1*}, \text{ for all } s \in (0,1], \ i = 1,...,4. \tag{25}$$

If there is no climate change damage, i.e., $s = 0,$ the four nations do not gain by moving from setting 1 ({1,2}, {3,4}) in which continental sulfur externalities are fully internalized through the two continental agreements to setting 7 in which the four nations maximize global welfare. If there are damages caused by the greenhouse gas emissions, i.e., $s \in (0,1],$ setting 7 which induces full internalization of global climate change externalities and continental acid rain externalities produces higher global welfare than setting 1 which induces internalization of only continental acid rain externalities. Since all nations' payoffs are equalized in both settings, every country is better off in setting 7 than in setting 1.

Then we compare a nation's payoff in setting 1 with the nation's payoffs in other inefficient settings where it joins an IEA. Combining equations (7c) and (8d) yields

$$u^{1*} = u_j^{2*}, \text{ if } s = 0; \text{ and } u^{1*} > u_j^{2*}, \text{ for all } s \in (0,1], \ j = 1,2. \tag{26a}$$

Without climate change damage, i.e., $s = 0,$ a nation in setting 1 achieves the same payoff as in setting 2 ({1,2},{3},{4}) in which it joins a continental coalition while the two nations in the other region stay as singletons. In both settings, the nation and its neighbor in the same region internalize continental sulfur externalities and its welfare is not affected by the energy consumption choices made by nations in the other region. If there are damages caused by the greenhouse gas emissions, i.e., $s \in (0,1]$, the two singletons in setting 2 emit more greenhouse gas than in setting 1 in which they form a continental agreement according to equations (7a) and (8b). The global quantity of greenhouse gas emissions in setting 2 is hence higher than in setting 1 as shown by equations (7b) and (8c). Thus a member of a continental coalition in setting 1 will be negatively affected if the other continental coalition dissolves.

Comparing equations (7c) with equations (11c) yields

$$u^{1*} > u_i^{3*}, \quad i = 1,...,4, \text{for all } s \in [0,1]. \tag{26b}$$

Due to the continental acid rain problems caused by sulfur emissions, the continental agreements make every nation better off relative to setting 3 ({1,3}, {2,4}) in which the bilateral inter-continental agreements fail to address regional acid rain problems.

Combining equations (7c) and (12e) yields

$$u^{1*} > u_h^{4*}, \text{ for all } s \in [0,1], \ h = 1,3. \tag{26c}$$

A nation is better off in setting 1 than in setting 4 ({1,3},{2},{4}) in which it forms a bilateral agreement with a country in the other region and the other two countries act as singletons. In setting 4, the nation loses the benefits of reducing sulfur damages and suffers higher global greenhouse gas emissions as the two singleton countries increase their emissions of the greenhouse gas relative to setting 1 (see equations (7a), (7b), (12b) and (12c)).

Comparing equations (7c) and (17f) shows that

$$u^{1*} > u_l^{5*}, \quad l = 1,2,3, \text{ for all } s \in [0,1]. \tag{26d}$$

A nation is better off in setting 1 than in setting 5 ({1,2,3},{4}) in which it joins the trilateral agreement since one member of the trilateral agreement loses the benefits of reducing sulfur damages through a continental coalition.

The results of (26a) – (26d) inform us that

$$u^{1*} = \max\left\{u^{1*}, u_1^{2*}, u_1^{3*}, u_1^{4*}, u_1^{5*}\right\}, \text{ for all } s \in [0,1]. \tag{27}$$

Thus, setting 1 with two continental agreements produces the highest level of welfare for a non-singleton nation among all inefficient coalition structures in which at least one coalition is formed. In the presence of continental sulfur externalities, selecting the country in the same region as a coalitional partner seems a natural coalitional choice for a nation considering joining an IEA. Setting 1 where all nations do so performs in welfare terms only next to the efficient setting 7 for a non-singleton nation among all coalition structures in which at least one IEA is formed.

To examine whether setting 7 is stable, we also need to compare a nation's payoff in setting 7 and in settings in which it behaves as a singleton. Since each nation's payoff in setting 7 is no lower than the nation's payoff in setting 1, we check the stability of setting 7 by comparing a nation's payoff in setting 1 and in settings in which it behaves as a singleton so that we can identify conditions under which setting 7 is stable and setting 1 is the next best choice for all nations. According to equations (7c) and (3c),

$$u^{1*} > u^0 \quad \forall s \in [0,1]. \tag{28}$$

In setting 0, all nations choose energy consumption Nash non-cooperatively. Each nation gets a higher payoff in setting 1 by internalizing continental sulfur externalities.

We also find whether a nation's payoff in setting 1 is higher than its payoff in a setting in which at least one IEA is formed and in which it acts individually (settings 2, 4 and 5) depends on the magnitude of the damage-relativity index s. Equations (7c) and (8e) allow us to derive that

$$u^{1*} > u_k^{2*},\ k = 3,4,\ \text{if}\ s = 0; \tag{29a}$$

$$u^{1*} \geq u_k^{2*},\ k = 3,4,\ \forall s \in (0,1]\ \text{and}\ c \geq 7.873275; \tag{29b}$$

$$u^{1*} \geq u_k^{2*},\ k = 3,4, \text{if}\ 0 < s \leq \bar{s} \in (0,1)\ \text{and}\ c < 7.873275. \tag{29c}$$

In the absence of climate change damages, i.e., $s = 0$, a nation prefers setting 1 to setting 2 ({1,2},{3},{4}) in which it stays as a singleton and fails to deal with regional acid rain problems. When there are climate change damages, i.e., $s \in (0,1]$, being a singleton in setting 2 allows a nation to free ride on the other region's greenhouse gas emission abatement effort. The nation would compare the benefits of reduced acid rain damages produced by setting 1 with the benefits of higher energy consumption through free riding in setting 2. When energy consumption benefits are large, i.e., $c < 7.873275$, continental sulfur damages must be sufficiently large (i.e., the damage relativity index s must be smaller than a threshold value $\bar{s} \in (0,1)$) so that staying in setting 1 is more attractive to a nation than being a singleton in setting 2. For example, if $c = 4$, we have $u^{1*} \geq u_k^{2*}$, $k = 3,4$, if and only if $0 < s \leq \bar{s} = 0.647446568$. By contrast, when energy consumption benefits are small, i.e., $c \geq 7.873275$, the results in (29b) tell us that joining a continental environmental agreement in setting 1 is more beneficial to a country than acting as a singleton in setting 2.

Similar reasoning applies to the comparison between a nation's payoff in setting 1 and in setting 4 ({1,3},{2},{4}) as a singleton, and applies to the comparison between a nation's payoff in setting 1 and in setting 5 ({1,2,3},{4}) as a singleton. Equations (7c) and (12f) tell us that

$$u^{1*} > u_l^{4*},\ l = 2,4,\ \text{if}\ s = 0; \tag{30a}$$

$$u^{1*} \geq u_l^{4*},\ l = 2,4, \quad \forall s \in (0,1] \text{ and } c \geq 9.207633; \tag{30b}$$

$$u^{1*} \geq u_l^{4*},\ l = 2,4, \text{ if } 0 < s \leq \bar{s} \in (0,1) \text{ and } c < 9.207633. \tag{30c}$$

Comparing equations (7c) and (17g) reveals that

$$u^{1*} > u_4^{5*}, \text{ if } s = 0; \tag{31a}$$

$$u^{1*} \geq u_4^{5*}, \text{ if } 0 < s \leq \bar{s} \in (0,1). \tag{31b}$$

The result in (31b) informs us that regardless of the value of c, continental sulfur damages must be strong enough so that a nation prefers setting 1 to being a singleton in setting 5.

By comparing equations (3c), (8e), (12f) and (17g), we also have the following results:

$$u_4^{5*} = \max\{u^0, u_4^{2*}, u_4^{4*}, u_4^{5*}\}, \quad \forall s \in [0,1], \tag{32}$$

which states that a singleton country obtains the highest payoff in setting 5 than in other settings.

Combining the results in (25), (27), (31) and (32) yields

$$u^{7*} = \max\{u^0, u^{1*}, u_i^{2*}, u_i^{3*}, u_i^{4*}, u_i^{5*}, u^{7*}\}_{i=1,\ldots,4}, \quad \forall s \in (0, \bar{s}), \text{ where } \bar{s} \in (0,1). \tag{33a}$$

$$u^{1*} = \max\{u^0, u^{1*}, u_i^{2*}, u_i^{3*}, u_i^{4*}, u_i^{5*}\}_{i=1,\ldots,4}, \quad \forall s \in (0, \bar{s}), \text{ where } \bar{s} \in (0,1). \tag{33b}$$

Hence, we have the following proposition:

Proposition 2. There exists $\bar{s} \in (0,1)$ so that an efficient coalition structure is stable for any $0 < s \leq \bar{s}$. Furthermore, setting 1 which features two continental agreements is the second-best coalition structure for any $0 < s \leq \bar{s}$.

Proposition 2 informs us that an efficient coalition structure produces the highest payoff for every nation than any other inefficient coalition structures, including coalition structures that feature singletons. This is remarkable because no nation has an incentive to be a stand-alone nation! The condition for stability is that continental sulfur damages must be sufficiently high relative to climate change damages. When nations care about both climate change and regional transnational air pollution, large damages caused by regional transnational air pollution can prevent them from deviating from an efficient structure and free riding on the efforts of other countries to reduce climate change. Therefore, our efficient structures can be stable even in the d'Aspremont stability sense because no single country would like to deviate when other countries keep their coalitional choices.

It must be pointed out that this stability in the d'Aspremont sense cannot be achieved without taking into account the correlation between controlling greenhouse gases and air pollution. If continental sulfur damages are dropped from a representative consumer's utility function and the nations only set policies to deal with greenhouse gas emissions, we find that a nation will see the payoff generated by the stand-alone case in setting 5 higher than the payoff generated by setting 7 and the nation will decide to deviate from setting 7 if it assumes the other three nations do not defect.[8]

4.2 Numerical Examples

Table 1 shows some examples of combinations of the values of c and s that lead to stable and efficient coalition structures. Let us first look at the values of $\bar{s}$ in the third row of Table 1. At each of the five values of c, we have $u^{1*} > u_4^{5*}$ for any s smaller than $\bar{s}$. The results in (27) – (31) tell us that for all $s \in [0,1]$, the payoff of a nation in setting 1 is higher than or equal to the payoffs of the nation in any other inefficient policy settings except in the singleton cases in settings 2, 4 and 5, when energy consumption benefits are large, i.e., $c < 7.873275$. We consider two such values of c in Table 1, namely, $c = 2.5$ and $c = 4$. In these cases, continental sulfur damages must be sufficiently large so that staying in

[8] A formal proof is available from the authors upon request.

setting 1 for a nation is more attractive than being a singleton in settings 2, 4 or 5. For example, if $c = 4,$ we have $u^{1*} \geq u_k^{2*}$, $k = 3,4,$ if and only if $0 < s \leq \bar{s} = 0.647446568;$ $u^{1*} \geq u_l^{4*}$, $l = 2,4,$ if and only if $0 < s \leq \bar{s} = 0.8996544;$ and $u^{1*} \geq u_4^{5*}$, if and only if $0 < s \leq \bar{s} = 0.030305785.$ These results are consistent with equations (32), i.e., $u^{1*} \geq u_4^{5*}$ ensures $u^{1*} \geq u_4^{2*}$ and $u^{1*} \geq u_4^{4*}$. Thus, a nation's payoff in setting 1 is higher than or equal to the nation's payoff in any other inefficient policy settings when $c = 4$ and $0 < s \leq \bar{s} = 0.030305785.$ Similarly, if $c = 2.5,$ we have $u^{1*} \geq u_k^{2*}$, $k = 3,4,$ if and only if $0 < s \leq \bar{s} = 0.510395;$ $u^{1*} \geq u_l^{4*}$, $l = 2,4,$ if and only if $0 < s \leq \bar{s} = 0.8120877;$ and $u^{1*} \geq u_4^{5*}$, if and only if $0 < s \leq \bar{s} = 0.028976604.$ Thus, a nation's payoff in setting 1 is higher than or equal to the nation's payoff in any other inefficient policy settings when $c = 2.5$ and $0 < s \leq \bar{s} = 0.028976604.$ According to (27) – (31), we also find that for all $s \in [0,1]$, the payoff of a nation in setting 1 is higher than or equal to the payoffs of the nation in any other inefficient policy settings except in the stand alone case in setting 5, when energy consumption benefits are small, i.e., $c \geq 9.207633.$ We consider three such values of c in Table 1, namely, $c = 9.207633,$ $c = 12$ and $c = 16$. For the payoff of a nation in setting 1 to be also higher than the nation's payoff in the stand alone case in setting 5 at these three values of c, continental sulfur damages must be sufficiently large, i.e., the damage relativity index must be smaller than 0.031617124, 0.031856082, or 0.032053861, respectively, as shown by the last three cells in the third row of Table 1.

Since $u^{7*} \geq u^{1*}$ for all $s \in [0,1]$ according to (25), every country will be better off in an efficient coalition structure than in any inefficient coalition structures if a nation's payoff in setting 1 is higher than or equal to the nation's payoffs in any other inefficient policy settings. No country or coalitions of countries will have an incentive to leave an efficient setting to enter an inefficient one and an efficient coalition structure will therefore be a stable coalition structure. The values of $\bar{s}$ below which $u^{1*} \geq u_4^{5*}$ in the third row of Table 1 hence give us the range of s values at which an efficient coalition structure is stable and setting 1 is the second best choice for every nation at a given value of c.

Consider now the values of $\bar{s}$ in the fourth row of Table 1. At each of the five values of c, $u^{7*} > u_4^{5*}$ for any s smaller than $\bar{s}$. The comparison results in (32) tell us if $u^{7*} > u_4^{5*}$, a nation's payoff in setting 7 is higher than or equal to the payoffs of the nation in any other inefficient policy settings in which it acts as a singleton. The comparison results in (25) and (27) tell us that a nation's payoff in setting 7 is higher than or equal to the nation's payoffs in other inefficient settings in which it joins a coalition. Therefore, at a given value of c, the payoff of a nation in an efficient setting is higher than or equal to the payoffs of the nation in any inefficient policy settings at values of s below $\bar{s}$ in the fourth row and an efficient setting is stable. Since $u^{7*} \geq u^{1*}$ for all $s \in [0,1]$ according to (25), in order to achieve $u^{7*} \geq u_4^{5*}$, we do not need the level of continental sulfur damages to be as high as the level of these damages which leads to $u^{1*} \geq u_4^{5*}$ at any given value of c. Hence, the threshold values of the damage relativity index below which $u^{7*} > u_4^{5*}$ in the fourth row of Table 1 are higher than the threshold values of the damage relativity index below which $u^{1*} > u_4^{5*}$ in the third row of Table 1. And because of this, setting 1 is not necessarily the second best choice for every nation at values of s below $\bar{s}$ in the fourth row.

For the second row of Table 1, since $u_l^{5*} < u^{1*}$, $l = 1,2,3$, for all $s \in [0,1]$, in order to have $u_l^{5*} \geq u_4^{5*}, l = 1,2,3,$ the level of continental sulfur damages must be higher than the level of these damages which leads to $u^{1*} \geq u_4^{5*}$ at a given value of

c. Hence, the threshold values of s below which $u_l^{5*} > u_4^{5*}$, $l = 1,2,3,$ in the second row of Table 1 are lower than the threshold values of s below which $u^{1*} > u_4^{5*}$ in the third row of Table 1. Since the values of $\bar{s}$ in the second row are smaller than the values of $\bar{s}$ in the third row and in the fourth row at any given c in the table, we find that at a given value of c, for any s smaller than $\bar{s}$ in the second row, an efficient coalition structure is stable, setting 1 is the second best choice for the nations, and the payoff of a nation from forming a trilateral agreement in setting 5 is higher than the nation's stand-alone payoff in setting 5.

We also see that as the parameter c becomes larger in Table 1, the value of $\bar{s}$ increases in each row of rows 2, 3 and 4, which indicates that the level of continental sulfur damages needed to overcome free riding incentives gets lower as energy consumption benefits decrease.

5. Conclusions

We examine the stability of international environmental policy schemes when sovereign nations set policies to control both greenhouse gas emissions and traditional air pollutants. An international environmental policy scheme is defined to be stable if no country can obtain higher payoff under other international environmental policy schemes. We assume that within a coalition, the member countries and the income-transfer agency play a two stage game. In the first stage, the member countries choose national environmental policy Nash non-cooperatively. In the second stage, the income-transfer agency implements transfers across the member countries based on a payoff function obeying the Nash bargaining form. In addition to the grand coalition which contain all countries in the world, there are a large set of efficient policy schemes in which all nations join at least one coalition, there is no coalition containing all nations, and all nations' payoffs are positively connected through coalitions with overlapping member countries. We find whether the efficient policy schemes are stable depends on the relative magnitude of damages suffered by a country caused by climate change and caused by regional transnational air pollution. Large regional transnational air pollution damages relative to climate change damages can deter free riding because a nation may find it worse off deviating from an efficient policy scheme and suffering higher transnational air pollution.

To our knowledge, this is the first work in the IEA literature that simultaneously considers IEAs fighting climate change and controlling regional transnational air pollution. There is much scope for future work to improve our understanding of the interplay of controlling correlated regional and global pollution damages and the stability of IEAs. For example, we assume symmetric countries for simplicity and to highlight that the free riding incentive can be overcome when countries set both climate change and air pollution policies. An immediate next step would be to consider asymmetric countries. Other fruitful extensions are to consider bargaining costs in the negotiations that lead to the formation of IEAs and to examine settings with a large number of regions and countries.

References

AEA Technology plc. 2011. "Cost Benefit Analysis for the Revision of the National Emission Ceilings Directive: Policy Options for Revisions to the Gothenburg Protocol to the UNECE Convention on Long-Range Transboundary Air Pollution." **Holland, Mike, Anne Wagner, Fintan Hurley, Brian Miller and Alistair Hunt.** AEA/ED47788 Final Issue 2.

Barrett, Scott. 1994. "Self-Enforcing International Environmental Agreements." *Oxford Economic Papers*, 46 (Special Issue on Environmental Economics): 878-894.

Bollen, Johannes, Bruno Guay, Stéphanie Jamet, and Jan Corfee-Morlot. 2009. "Co-Benefits of Climate Change Mitigation Policies: Literature Review and New Results." OECD Economics Department Working Papers 693. doi: 10.1787/224388684356.

Caplan, Arthur. J., Richard C. Cornes, and Emilson C. D. Silva. 2003. "An Ideal Kyoto Protocol: Emissions Trading, Redistributive Transfers and Global Participation." *Oxford Economic Papers*, 55 (2): 216-234.

Caplan, Arthur. J., and Emilson C. D. Silva. 2005. "An Efficient Mechanism to Control Correlated Externality: Redistributive Transfers and the Coexistence of Regional and Global Pollution Permit Markets." *Journal of Environmental Economics and Management*, 49 (1): 68-82.

Carraro, Carlo, and Domenico Siniscalco. 1993. "Strategies for the International Protection of the Environment." *Journal of Public Economics*, 52 (3): 309-328.

Chander, Parkash. 2003. "The γ -Core and Coalition Formation." Université catholique de Louvain, Center for Operations Research and Econometrics (CORE) Discussion Papers 2003/46.

Chander, Parkash, and Henry Tulkens. 1995. "A Core-Theoretic Solution for the Design of Cooperative Agreements on Transfrontier Pollution." *International Tax and Public Finance*, 2 (2): 279-93.

Chander, Parkash, and Henry Tulkens. 1997. "The Core of an Economy with Multilateral Environmental Externalities." *International Journal of Game Theory*, 26 (3): 379-401.

Chander, Parkash, and Henry Tulkens. 2006. "Cooperation, Stability and Self-Enforcement in International Environmental Agreements: a Conceptual Discussion." Université catholique de Louvain, Center for Operations Research and Econometrics (CORE) Discussion Papers 2006/03.

Chestnut, Lauraine G.**, and David** M. **Mills.** 2005. "A Fresh Look at the Benefits and Costs of the US Acid Rain Program." *Journal of Environmental Management*, 77 (3): 252-266.

Chwe, Michael S.-Y. 1994. “Farsighted Coalitional Stability.” *Journal of Economic Theory*, 63 (2): 299-325.

D’Aspremont, Claude, Alexis Jacquemin, Jean. J. Gabszewicz, and John. A. Weymark. 1983. “On the Stability of Collusive Price Leadership.” *Canadian Journal of Economics*, 16 (1): 17-25.

Department for Environment, Food and Rural Affairs (Defra), United Kingdom. 2010. “Air Pollution: Action in a Changing Climate.” http://www.defra.gov.uk/publications/files/pb13378-air-pollution.pdf.

Diamantoudi, Effrosyni, and Eftichios Sartzetakis. 2002. “International Environmental Agreements: the Role of Foresight.” Department of Economics, University of Aarhus, Denmark, Working Paper 2002 – 10.

European Environmental Agency (EEA). 2004. “Air Pollution and Climate Change Policies in Europe: Exploring Linkages and the Added Value of an Integrated Approach.” Technical Report No.5.

Eyckmans, Johan. 2001. “On the Farsighted Stability of the Kyoto Protocol.” Katholieke Universiteit Leuven, Center for Economic Studies, Energy, Transport and Environment, Energy, Transport and Environment Working Papers Series ete01-03.

Eyckmans, Johan, **and Michael Finus.** 2003. “Coalition Formation in a Global Warming Game: How the Design of Protocols Affects the Success of Environmental Treaty-Making.” Université catholique de Louvain, Center for Operations Research and Econometrics (CORE) Discussion Papers 2003/088.

Eyckmans, Johan, **and Henry Tulkens.** 2003. “Simulating Coalitionally Stable Burden Sharing Agreements for the Climate Change Problem.” *Resource Energy Economics*, 25 (4): 299-327.

Finus, Michael. 2008. “Game Theoretic Research on the Design of International Environmental Agreements: Insights, Critical Remarks and Future

Challenges." *Intentional Review of Environmental and Resource Economics*, 2 (1): 29 – 67.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*: **McCarthy, James J., Osvaldo F. Canziani, Neil A. Leary, David J. Dokken, and Kasey S. White** (eds.). Cambridge, UK: Cambridge University Press.

Mariotti, Marco. 1997. "A Model of Agreement in Strategic Form Games." *Journal of Economic Theory*, 74 (1): 196-217.

Mariotti, Marco, and Licun Xue. 2003. "Farsightedness in Coalition Formation" in *The Endogenous Formation of Economic Coalitions*: **Carraro, Carlo** (ed.). Cheltenham: Edward Elgar.

Osmani, Dritan, and Richard S.J. Tol. 2009. "Toward Farsightedly Stable International Environmental Agreements." *Journal of Public Economic Theory*, 11 (3): 455-492.

Silva, Emilson C.D., and Xie Zhu. 2009. "Emissions Trading of Global and Local Pollutants, Pollution Havens and Free Riding." *Journal of Environmental Economics and Management*, 58 (2): 169-182.

Silva, Emilson C.D., and Xie Zhu. 2011. "Efficient International Environmental Agreements for Correlated Transnational Pollutants in the Presence of Free Trade of Goods and International Transfers." *Strategic Behavior and the Environment*, 1 (2): 175-197.

US Environmental Protection Agency (EPA). 2011. "The Benefits and Costs of the Clean Air Act from 1990 to 2020: Summary Report." http://www.epa.gov/air/sect812/feb11/summaryreport.pdf.

Xue, Licun. 1998. "Coalitional Stability under Perfect Foresight." *Economic Theory*, 11 (3): 603-627.

Table 1: Examples of c and $\bar{s}$ that result in efficient and stable coalition structures.

c	**2.5**	**4**	**9.207633**	**12**	**16**
value of $\bar{s}$ below which $u_j^{5*} > u_4^{5*}$, $j = 1,2,3$	0.012379	0.012802	0.013184488	0.01324963	0.013302265
value of $\bar{s}$ below which $u^{1*} > u_4^{5*}$	0.028976604	0.030305785	0.031617124	0.031856082	0.032053861
value of $\bar{s}$ below which $u^{7*} > u_4^{5*}$	0.03264464	0.03515371	0.038269162	0.038952368	0.039556962

Appendix A: Derivation of Equations (12a) and (12b) (*For Online Publication*)

With $a_1 = a_2 = (e_1 + e_2)/2$ and $a_3 = a_4 = (e_3 + e_4)/2$, equations (10e) for nations 1 and 3 can be rearranged to yield

$$\left(2c + \frac{1}{2}\right)(e_1 - e_3) = \frac{1}{2}(e_4 - e_2), \tag{A1}$$

and equation (2a) for nation 2 and equation (2b) for nation 4 can be rearranged to yield

$$\left(2c + \frac{1}{2}\right)(e_4 - e_2) = \frac{1}{2}(e_1 - e_3). \tag{A2}$$

Equations (A1) and (A2) indicate that $e_4 - e_2 = e_1 - e_3$. Substituting $e_4 - e_2 = e_1 - e_3$ into equation (A1) results in $2c(e_1 - e_3) = 0$, which implies $e_1 = e_3$ since $c \neq 0$. Plugging this result into either equation (A1) or (A2) yields $e_2 = e_4$. Hence, $g = 2(e_1 + e_2)$. Plugging $g = 2(e_1 + e_2)$ into equation (10e) for nation 1 and equation (2a) for nation 2, adding the implied expressions and solving for $e_1 + e_2$ yield $e_1 + e_2 = 2(b-1)/(1 + 2c + 12s)$. Combining this result with equation (10e) for nation 1 and taking into account that $e_1 = e_3$ and $g = 2(e_1 + e_2)$ yield equations (12a); combining this result with equation (2a) for nation 2 and taking into account that $e_2 = e_4$ and $g = 2(e_1 + e_2)$ yield equations (12b).